Letters

Low Common Mode Noise Half-Bridge *LLC* DC–DC Converter With an Asymmetric Center Tapped Rectifier

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***Abstract*—Half-bridge *LLC* dc–dc converter is popular in electric vehicle on-board charger due to its soft switching, high-power density, and low cost. But, it also has serious electromagnetic interference problems in that the half-bridge structure brings asymmetry common mode (CM) noise source by switching. So, this letter proposes an asymmetric center tapped rectifier (ACTR) to reduce the CM noise in half-bridge *LLC* without additional components. With ACTR, the CM noise source on primary winding is cancelled by CM noise sources on secondary windings. The CM noise reduction of the proposed ACTR is verified by a 1.1-kW half-bridge *LLC* prototype with 800 V input and 300–450 V output.**

***Index Terms*—Asymmetric center tapped rectifier (ACTR), common mode (CM) noise, half-bridge *LLC*.**

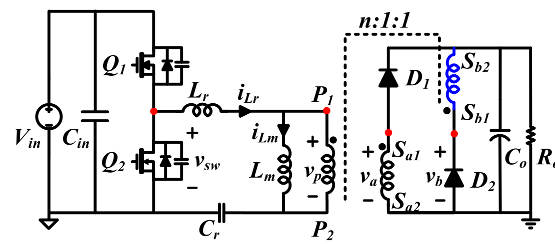

Fig. 1. Half-bridge LLC dc–dc converter with ACTR.

I. Introduction

THE half-bridge *LLC* dc–dc converter is popular in high-output voltage applications, such as electric vehicle battery chargers due to its soft switching, high power density, and low-cost characteristics [1]–[5]. But, unlike natural symmetric structure in full-bridge *LLC* [6], the asymmetric common mode (CM) noise source caused by half-bridge structure on primary side brings serious electromagnetic interference (EMI) problems.

Several techniques have been proposed to reduce the CM noise in the half-bridge *LLC* converter. A balance method is used to reduce the CM noise by generating a balanced Wheatstone bridge network in [7]. Usually balanced capacitors or inductors are added to satisfy the balance condition and are very sensitive to the tolerance. An out-of-phase voltage or current source to cancel the CM noise was introduced in [8]–[12]. In [8], an auxiliary transformer winding was added to generate the cancellation voltage source. In [9], compensate capacitors were added to the transformer to introduce an out-of-phase CM current. In [10] and [11], shielding layers were inserted and proper connected to cancel the CM noise voltage sources on secondary windings. In [12], two-phase interleaved half-bridge *LLC* converters with 180° phase shift were adopted to cancel the CM noise voltage sources by each other. Clearly, all these techniques required additional components, which increase the cost and complexity.

In this letter, an asymmetric center tapped rectifier (ACTR) is proposed to reduce the CM noise in the half-bridge *LLC* converter based on CM voltage sources cancellation of primary and secondary windings without adding any components compared with the conventional center tapped rectifier (CTR).

II. CM Noise Comparison in Half-Bridge *LLC* With ACTR and CTR

The schematic of the proposed half-bridge *LLC* dc–dc converter with ACTR is shown in Fig. 1. $P(P_1 - P_2)$ is the primary winding, and $S_a(S_{a1} - S_{a2})$ and $S_b(S_{b1} - S_{b2})$ are secondary windings. Compared with the conventional CTR, winding S_b and diode D_2 exchange their location in ACTR.

Considering C_r, C_{in}, and C_o as short circuit in EMI frequency range, there are in total four voltage pulsation sources that contribute to CM noise in half-bridge *LLC* shown in Fig. 1, such as the primary half-bridge switching node voltage v_{sw}, voltage across the primary winding v_p, and secondary side switching node voltages v_a and v_b. Since the parasitic capacitance between the primary half-bridge switching node and the ground is small, the influence of v_{sw} is neglected.

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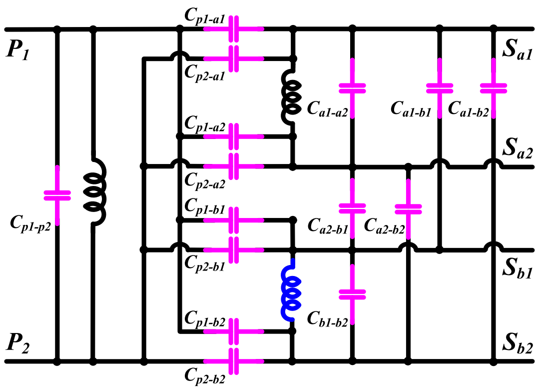


Fig. 2. Lumped model of the transformer.

The parasitic capacitances of transformer provide CM noise paths. Many literatures analyzed the lumped model of the transformer [12]–[14]. The most commonly used model in [12] is adopted here. The lumped model of the transformer is shown in Fig. 2, in which there are in total 15 parasitic capacitances for a three-winding transformer. Then, according to the key waveforms for the half-bridge *LLC* converter with ACTR shown in Fig. 3(a), an equivalent CM coupling circuit is derived, as shown in Fig. 3(b). It can be seen that C_{p1-p2} is directly connected to v_p, so based on the superposition theory, the displacement current caused by this capacitor circulates in v_p and does not contribute to the CM noise. Thus, C_{p1-p2} is ignored. Due to the same reason, C_{a1-a2}, C_{b1-b2}, C_{a2-b2}, C_{a1-b1}, C_{a2-b1}, and C_{a1-b2} are not included in the simplified model [12]. So, there are only eight capacitances in the simplified model, as shown in Fig. 3(c).

It should be noted that the line impedance stabilization network can be considered as short circuit because of its small impedance in CM coupling circuit. Since C_r is treated as short circuit and P_2, S_{a2}, and S_{b2} are connected to the input or output capacitor in the proposed converter, their voltage potential can be seen as stable. Thus, there is no displacement current through C_{p2-a2} and C_{p2-b2}, and they do not conduct the CM noise. So, C_{p2-a2} and C_{p2-b2} are ignored. Then, based on the superposition theory, the CM current i_{CM} caused by v_p, v_a, and v_b is respectively calculated in the following equations:

$$i_{\text{CM}-p} = (C_{p1-a1} + C_{p1-a2} + C_{p1-b1} + C_{p1-b2})\,\frac{dv_p}{dt} \quad (1)$$

$$i_{\text{CM}-a} = -\,(C_{p1-a1} + C_{p2-a1})\,\frac{dv_a}{dt} \quad (2)$$

$$i_{\text{CM}-b} = -\,(C_{p1-b1} + C_{p2-b1})\,\frac{dv_b}{dt}. \quad (3)$$

The total CM current can be calculated by adding (1)–(3) as follows:

$$i_{\text{CM-ACTR}} = (C_{p1-a1} + C_{p1-a2} + C_{p1-b1} + C_{p1-b2})\,\frac{dv_p}{dt} - \left[(C_{p1-a1} + C_{p2-a1})\,\frac{dv_a}{dt} + (C_{p1-b1} + C_{p2-b1})\,\frac{dv_b}{dt}\right]. \quad (4)$$

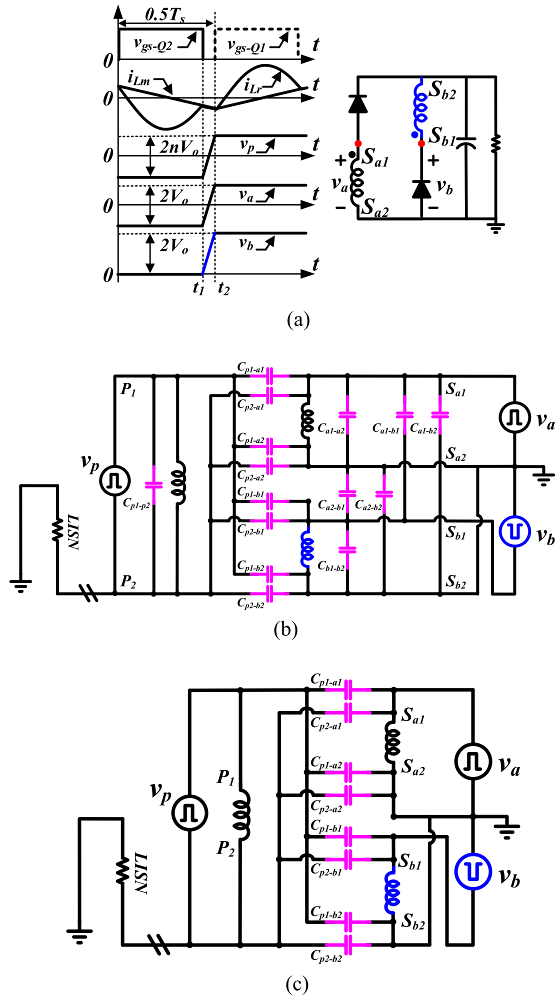


Fig. 3. Half-bridge *LLC* with ACTR. (a) Key waveforms. (b) Equivalent CM coupling circuit. (c) Simplified equivalent CM coupling circuit.

It is clear that the CM current caused by v_p can be cancelled by the CM current caused by v_a and v_b. Based on the key waveforms in Fig. 3(a), we have

$$\frac{dv_p}{dt} = n\frac{dv_a}{dt} = n\frac{dv_b}{dt} \quad (5)$$

where *n* is the turn ratio of the transformer. Thus, (4) can be further simplified as follows:

$$i_{\text{CM-ACTR}} = [(n-1)\,(C_{p1-a1} + C_{p1-b1}) + n\,(C_{p1-a2} + C_{p1-b2}) - (C_{p2-a1} + C_{p2-b1})]\,\frac{dv_a}{dt}. \quad (6)$$

If the transformer is made symmetrically, the values of C_{p1-a2}, C_{p1-b2}, C_{p2-a1}, and C_{p2-b1} can be treated as equal; then, if the turn ratio *n* is 1, i_{CM} can be fully canceled. It should be noted that even if C_{p1-a2}, C_{p1-b2}, C_{p2-a1}, and C_{p2-b1} are not of the same value, or *n* is not equal to 1, there is still cancelation effect and i_{CM} can be reduced drastically according to (4).

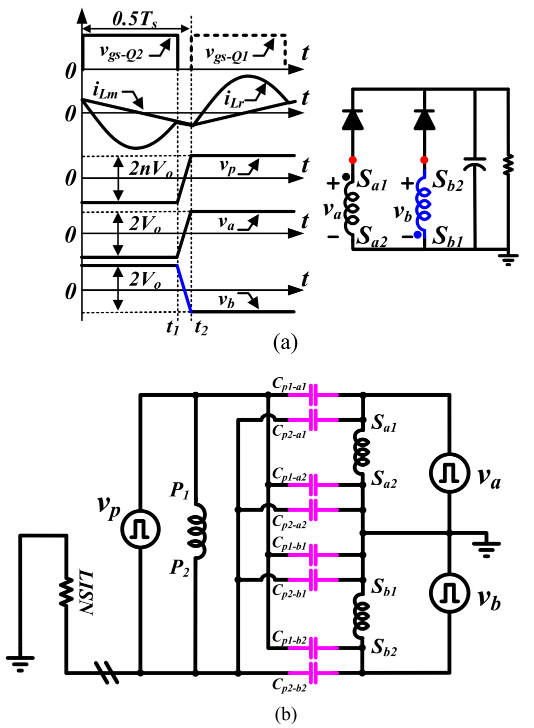


Fig. 4. Half-bridge *LLC* with CTR. (a) Key waveforms. (b) Equivalent CM coupling circuit.

For the half-bridge *LLC* converter with conventional CTR, the key waveforms and the equivalent CM coupling circuit are shown in Fig. 4(a) and (b), respectively. Obviously, the *dv/dt* of v_b has opposite phase compared with ACTR, as shown in Fig. 3(a) and (b). Since only v_b has changed, the CM current caused by it is recalculated based on the superposition theory

$$i_{\mathrm{CM}-b} = (C_{p1-b2} + C_{p2-b2})\,\frac{dv_b}{dt}. \tag{7}$$

Then, the total CM current i_{CM} can be obtained by adding (1), (2), and (7)

$$i_{\mathrm{CM-CTR}} = (C_{p1-a1} + C_{p1-a2} + C_{p1-b1} + C_{p1-b2})\,\frac{dv_p}{dt} - \left[(C_{p1-a1} + C_{p2-a1})\,\frac{dv_a}{dt} - (C_{p1-b2} + C_{p2-b2})\,\frac{dv_b}{dt}\right]. \tag{8}$$

If the transformer is made symmetrically, which is usually satisfied in the conventional CTR structure, C_{p1-a1} is equal to C_{p2-b2} and C_{p2-a1} is equal to C_{p1-b2}; thus, the CM currents caused by v_a and v_b are cancelled by each other. Then, (8) can be simplified as follows:

$$i_{\mathrm{CM-CTR}} = (C_{p1-a1} + C_{p1-a2} + C_{p1-b1} + C_{p1-b2})\,\frac{dv_p}{dt}. \tag{9}$$

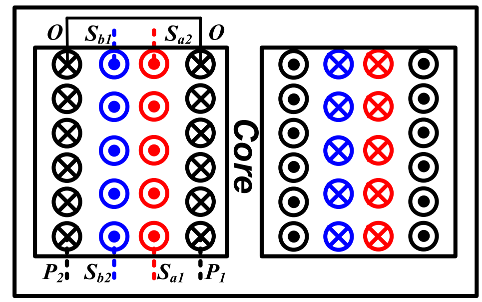


Fig. 5. Transformer winding structure.

TABLE I
TRANSFORMER SPECIFICATIONS

Core material	Ferrite DMR95
Core size	PQ32/30
Bobbin	PQ32/30
Primary winding	AWG 38, 50 strands*16turns
Secondary winding a	AWG 38, 50 strands*16turns
Secondary winding b	AWG 38, 50 strands*16turns

The CM current caused by v_p is no longer cancelled compared with (4). So, the CM noise in half-bridge *LLC* with CTR is larger than that in *LLC* with ACTR.

III. Experimental Results

A 1.1-kW half-bridge *LLC* prototype with 800 V input and 300–450 V output, which is used as the dc–dc part in the on-board charger [2], is built to demonstrate the analysis. The specification is also the same as that in [2]. The resonant frequency f_r is 340 kHz, and the nominal output voltage is 400 V. With variable frequency control, the switching frequency f_s ranges from 300 to 380 kHz. A typical symmetric transformer structure shown in Fig. 5 is adopted here as an example. In Fig. 5, half of the primary winding $(P_1 - O)$ is wounded first, then secondary windings S_a $(S_{a1} - S_{a2})$ and S_b $(S_{b2} - S_{b1})$ are wounded, and finally the other half of the primary winding $(P_2 - O)$ is wounded outside. This makes sure that $(C_{p1-a2} + C_{p1-b2})$ is equal to $(C_{p2-a1} + C_{p2-b1})$. It is to be noted that Fig. 5 only illustrates the winding arrangement, and the turns in each layer do not reflect the actual case.

A. CM Noise Reduction With Different Turn Ratios

When the turn ratio is set as 1:1:1 first, half of the primary winding has 8 turns and each secondary wingding has 16 turns. The specifications of the transformer are given in Table I. The waveforms of CM noise voltage sources v_p, v_a, and v_b at different f_s with ACTR are shown in Fig. 6. It can be seen that secondary side switching node voltage v_b is in phase with v_a, which matches the analysis in Section II. Moreover, the voltage across D_2, i.e., v_b, is still $2V_o$, which is the

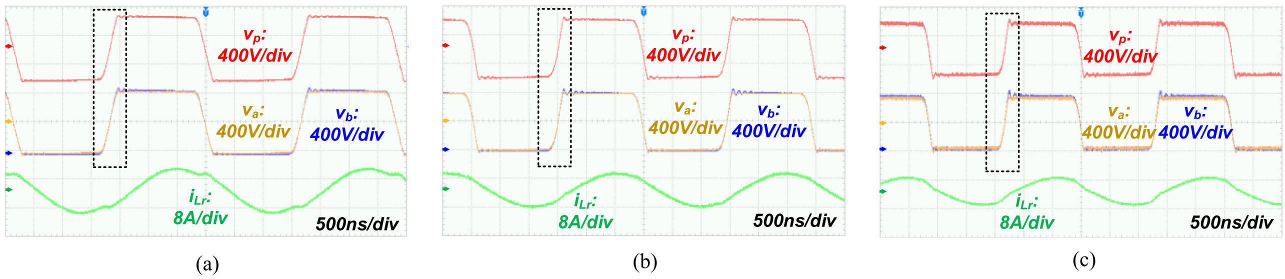


Fig. 6. Key waveforms of transformer terminations with ACTR when the turn ratio is 1:1:1. (a) DCM, $f_s = 300$ kHz. (b) CrM, $f_s = 340$ kHz. (c) CCM, $f_s = 380$ kHz.

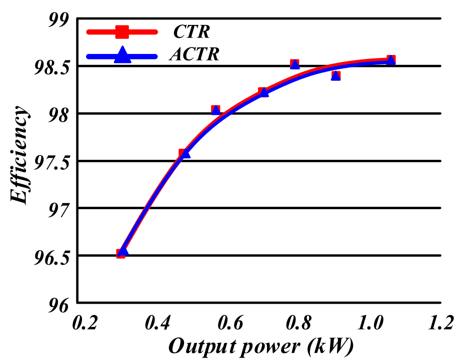


Fig. 7. Efficiency of the proposed *LLC* converter.

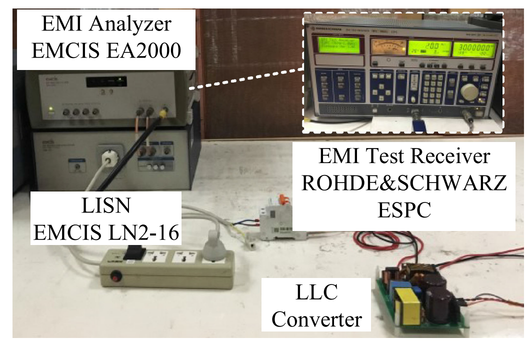


Fig. 8. Test environment setup.

same as that in conventional *LLC* with CTR. And, the efficiency of the proposed *LLC* converter with ACTR shows almost no difference with conventional *LLC* with CTR, as shown in Fig. 7.

CM mode noise of the proposed *LLC* converter is tested, and the test environment setup is shown in Fig. 8. From the measured CM noise spectra without filter at different f_s, shown in Fig. 9, we can see that with the proposed ACTR, the CM noise is reduced both for fundamental and high-order harmonics compared with CTR.

Except for the CM noise conducted by the parasitic capacitance of transformer, the measured spectra in Fig. 9 also contain the CM noise introduced by other parasitic capacitances (such as capacitance between primary and secondary heatsinks). This letter focuses on the influence of the parasitic capacitance of the transformer and does not consider other parasitic capacitances.

The dotted lines in Fig. 9 represent the trend of CM noise. Since there are many spectra, some peak values are not connected to this line to make sure the figure is clear to be read. Moreover, some peaks appear at frequencies that are not multiple of the switching frequency, which are considered as background noise caused by printed circuit board (PCB) layout. They appear in both *LLC* converters with proposed ACTR and conventional CTR, and there is barely any change on the peak value. These peaks do not affect the CM noise reduction and can be solved by proper PCB layout.

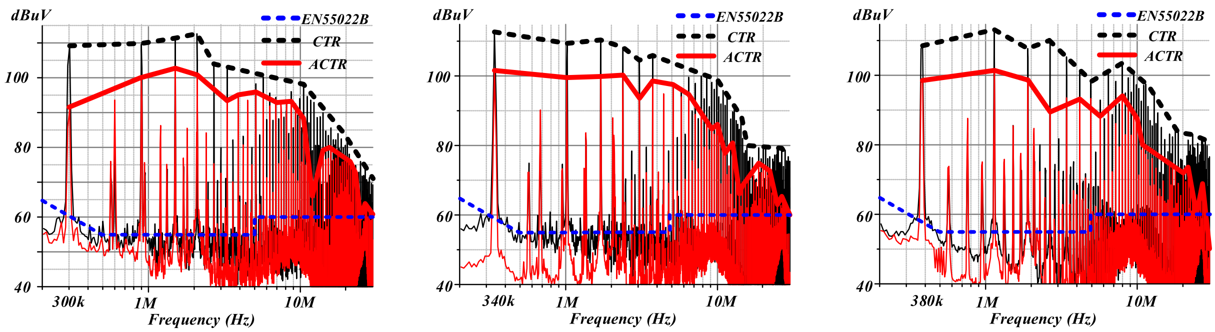
As analyzed in Section II, the efficiency of the proposed topology is concerned with the turn ratio of the transformer. Experimental results when the turn ratio is 2:1:1 are shown in this letter. Fig. 10 shows the waveforms of CM noise voltage sources v_p, v_a, and v_b at different f_s with ACTR. The secondary side switching node voltage v_b is in phase with v_a, so there is still cancellation effect on CM noise. Fig. 11 shows the measured CM noise spectra without filter at different f_s. The CM noise is still reduced for both fundamental and high-order harmonics compared with CTR, but the reduction is less compared with Fig. 9.

B. Expected CM Filter Size Reduction

Since the CM noise still does not satisfy the EMI standard EN55022B with the proposed ACTR, an EMI filter is needed. The CM filter size of *LLC* with CTR and ACTR is compared. According to [15], the required CM noise attenuate (insertion loss) is

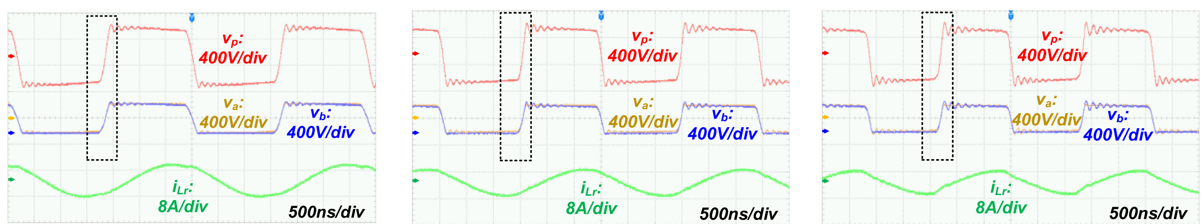
$$(V_{\text{req\_CM}})_{\text{dB}} = (V_{\text{CM}})_{\text{dB}} - (V_{\text{Limit}})_{\text{dB}} + 3\,\text{dB}. \qquad (10)$$

The peak value of the required insertion loss for three operating cases in Fig. 9 is shown in Fig. 12. For the one-stage *LC* CM filter, the corner frequencies are 13 and 27 kHz for the *LLC* converter with CTR and ACTR, respectively; for the two-stage *LCLC* CM filter, the corner frequencies are 65 and 95 kHz for the *LLC* converter with CTR and ACTR, respectively. Since the corner frequency is inversely proportional to the square root of inductance L times capacitance C ($\sqrt{LC}$), and assuming that the volume of the inductor and capacitor is proportional to their value [16], the filter size can be reduced by 51.9% and 31.6% for the one-stage *LC* CM filter and two-stage *LCLC* CM filter, respectively.



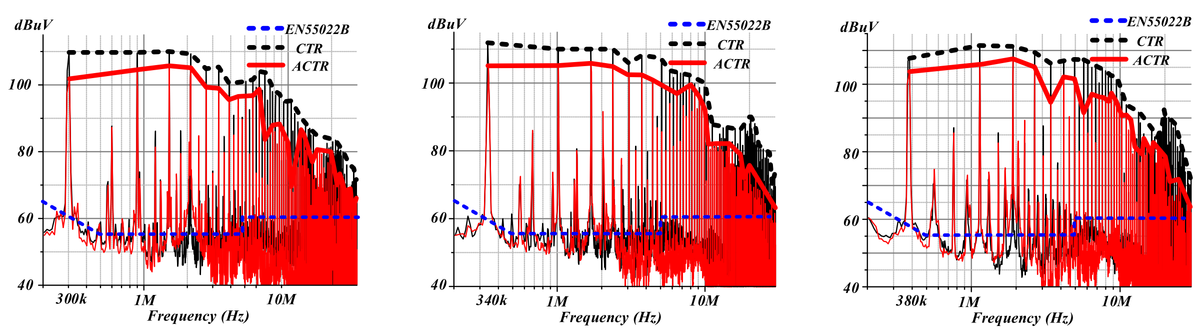
(a) (b) (c)

Fig. 9. Measured CM noise spectra when the turn ratio is 1:1:1. (a) DCM, $f_s = 300$ kHz. (b) CrM, $f_s = 340$ kHz. (c) CCM, $f_s = 380$ kHz.



(a) (b) (c)

Fig. 10. Key waveforms of transformer terminations with ACTR when the turn ratio is 2:1:1. (a) DCM, $f_s = 300$ kHz. (b) CrM, $f_s = 340$ kHz. (c) CCM, $f_s = 380$ kHz.



(a) (b) (c)

Fig. 11. Measured CM noise spectra when the turn ratio is 2:1:1. (a) DCM, $f_s = 300$ kHz. (b) CrM, $f_s = 340$ kHz. (c) CCM, $f_s = 380$ kHz.

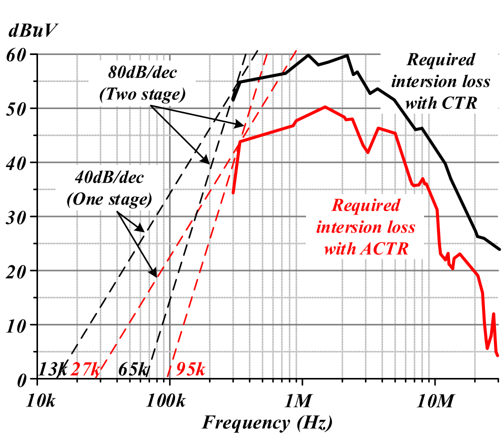


Fig. 12. Required insertion loss for the *LLC* converter with CTR and ACTR.

IV. Conclusion

A low CM noise half-bridge *LLC* dc–dc converter with ACTR is presented in this letter. The CM noise is reduced because of the cancellation of CM noise voltage sources on primary and secondary sides. Compared with the conventional CTR, half-bridge *LLC* with the proposed ACTR achieves lower CM noise without any additional components.

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